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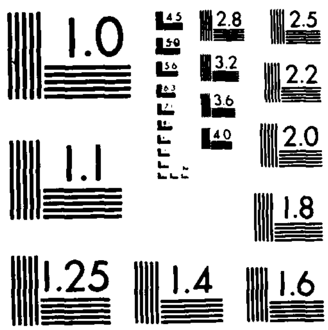

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Retrofit Control Systems for Energy Conservation

AD-A173 266

Measured Performance of Variable-Air-Volume Boxes

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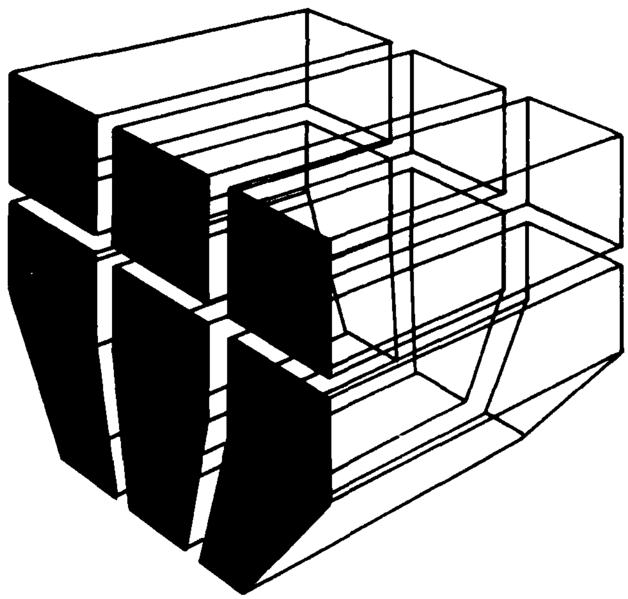
by
Lynn Krajnovich
Douglas C. Hittle

This report documents the results of work conducted to measure the performance of currently available variable-air-volume (VAV) boxes in terms of pressure independence, linearity, and hysteresis. This work was part of research being conducted to develop control systems for simple and reliable retrofit applications to heating, ventilating, and air-conditioning systems.

General conclusions of the study indicated that the performance characteristics of VAV boxes vary widely and that this variation is likely to continue until consistently applied manufacturing standards are implemented. The tests also showed that most VAV boxes do not quite meet the manufacturers' performance claims. A general problem is the boxes' inability to conform to specified minimum and maximum flow rates; although recalibration to give the desired flow rates is possible, it would be a difficult, time-consuming procedure in the field.



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This report documents the results of work conducted to measure the performance of currently available variable-air-volume (VAV) boxes in terms of pressure independence, linearity, and hysteresis. This work was part of research being conducted to develop control systems for simple and reliable retrofit applications to heating, ventilating, and air-conditioning systems.

General conclusions of the study indicated that the performance characteristics of VAV boxes vary widely and that this variation is likely to continue until consistently

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applied manufacturing standards are implemented. The tests also showed that most VAV boxes do not quite meet the manufacturers' performance claims. A general problem is the boxes' inability to conform to specified minimum and maximum flow rates; although recalibration to give the desired flow rates is possible, it would be a difficult, time-consuming procedure in the field.

FOREWORD

This research was conducted for the Office of the Assistant Chief of Engineers (OACE) under Project 4A162781AT45, "Basic Research in Military Construction"; Task B, "Energy Systems"; Work Unit 002, "Retrofit Control Systems for Energy Conservation." The work was performed by the Energy Systems Division (ES), U.S. Army Construction Engineering Research Laboratory (USA-CERL). Dr. Douglas C. Hittle was the USA-CERL Principal Investigator. Mr. B. Wasserman, DAEN-ZCF-U, was the OACE Technical Monitor. Dr. G. R. Williamson is Acting Chief of USA-CERL-ES.

COL Norman C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

Heating and cooling buildings makes up a large part of the Army's energy costs. Therefore, the Army is attempting to improve systems that will make its buildings as energy-conservative as possible. Problems with heating, ventilating, and air-conditioning (HVAC) controls are one factor that has caused a great deal of energy to be wasted.

The use of variable-air-volume (VAV) systems in HVAC control applications has become increasingly popular because VAV systems are more energy-efficient than constant-volume systems and are easily retrofitted to conventional systems. In VAV systems, airflow is modulated by a thermostatically controlled air-modulating box, called a VAV box. These boxes are located in the ductwork upstream of the room to be conditioned and are controlled through a pneumatic actuator connected to the room thermostat. Figure 1* illustrates a basic VAV box configuration.

The Army has recently begun to replace traditional HVAC systems with VAV systems. However, these applications have been characterized by poor control, inadequate ventilation, and poor flow modulation. Therefore, in an effort to make these systems more reliable, the U.S. Army Construction Engineering Research Laboratory (USA-CERL) was asked to conduct a series of tests designed to study and solve these problems.

Overall Objective

The objective of the overall research is to develop HVAC control systems, especially systems for retrofit applications, that are simple, efficient, reliable, maintainable, and well-documented. This research will be conducted in three main areas: (1) component evaluation, (2) control loop implementation, and (3) system applications.

Overall Approach

Laboratory and field studies are focusing on identifying a level of performance that can be expected from "typical" HVAC control equipment now in use. Control equipment most commonly used in process industries will be evaluated to determine its applicability to HVAC control problems.

Control components are combined to provide individual HVAC system control loops (for example, control of the discharge temperature from a cooling or heating coil). Several subsystem control loops are being studied to determine the best way to provide accurate control.

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*Figures begin on p 17.

To provide reliable, effective control systems, the results of component evaluation and control implementation studies must be combined to develop system applications guidance. Emphasis of the system applications research is on investigating the overall performance of heating and air-conditioning systems. Specifically being studied are the costs/benefits of various HVAC control retrofit schemes and the dynamics of combining various individual control loops.

Objective of This Study

The objective of this phase of the work was to measure the performance of available VAV boxes in terms of pressure independence, linearity, and hysteresis.

Approach of This Study

Sample VAV boxes obtained from three manufacturers were tested for pressure independence, linearity, and hysteresis. The data obtained were then statistically analyzed. The results were compared to determine the performance of each box.

Mode of Technology Transfer

The information in this report has been incorporated into draft Design Instructions and Technical Specifications prepared by USA-CERL. The results will also be included in a new Technical Manual and Guide Specification on HVAC Controls being prepared by the Corps of Engineers, Huntsville Division.

2 SAMPLES AND TESTING APPARATUS

Sample VAV boxes were obtained from three manufacturers for performance testing. Although several types of VAV boxes are available, the ones chosen were those whose volume flow is controlled by simple physical principles. In all the samples tested, the actuator was intended to be connected directly to the room thermostat rather than to be fed through more complex flow sensing and control systems. The boxes from manufacturer A used a spring and cone type system of air flow control (Figure 2). Manufacturer B used a butterfly damper and inflatable bladder type of setup (Figure 3). Manufacturer C chose a guillotine-type blade with a bellows to control airflow (Figure 4).

The testing apparatus used (Figure 5) consisted of a fan powered by a variable-speed 5-hp motor, which forced air into a length of 6-in. (152.4-mm)- diameter ductwork, which was long enough to allow airflow to develop fully. The box to be tested was mounted in the ductwork with lengths of flexible duct (Figure 6). The differential pressure across the box was controlled by the fan speed.

Static pressure taps were located immediately upstream and downstream of the test section to measure static pressure drop across the VAV box. Another length of ductwork ran from the sample to a plenum chamber. Nozzles ranging from 1 to 6 in. (25.4 mm to 152.4 mm) in diameter allowed air to exit from the chamber. The flow was determined by measuring the pressure drop across the nozzle being used (a static pressure tap was located just before the nozzle). Figure 7 shows details of the testing apparatus' instrument panel.

ARI Standard 880 and ADC Standard 1062 outline standard test procedures for VAV boxes. The apparatus and procedure used in this study roughly correspond to those outlined in the standards.

3 TESTING PROCEDURES

Pressure Independence

VAV boxes are ideally designed to provide constant flow over a specified range of differential pressures for a fixed actuator pressure. A thermostat in the room to which the VAV box is attached controls the actuator pressure, thereby controlling airflow to the room. Airflow to the room should be constant, despite varying pressure in the ductwork upstream of the VAV box. This characteristic is known as pressure independence.

To test for pressure independence, varying differential pressures corresponding to varying static pressures were applied across the VAV box. Varying actuator pressures were used to simulate different control signals from the room thermostat. Each VAV box was tested over the differential pressure and actuator pressure ranges specified by the manufacturer.

The steps in the test procedure were:

1. The actuator pressure was set to the minimum value specified by the manufacturer.

2. Fan speed was increased to produce a minimum specified value for the differential pressure across the box.

3. Several minutes were allowed for the system to settle. Then the differential pressure across the VAV box and the differential pressure across the nozzle were recorded.

4. The differential pressure of the test section was increased slightly.

5. The system was allowed to settle, and static pressure and differential pressure across the nozzle were recorded.

6. Steps 4 and 5 were repeated up to the maximum differential pressure recommended by the manufacturer.

7. Tests were repeated for a sufficient number of actuator pressures within the manufacturer's specifications.

8. Flow rate versus differential pressure were plotted for all tests on one set of axes.

9. Root mean square values for each data set were calculated to determine the standard deviation of the data from the associated mean line.

Linearity

Linearity refers to the relationship between the actuator pressure (controlled by the room thermostat) and the flow rate.

In a normal VAV application, static pressure to the main duct system is controlled by the control panel, which varies the speed of the supply fan and is thereby able to hold static pressure constant. The static pressure is set to an appropriate point to provide required flow for the worst-case load (i.e., all boxes providing maximum flow to their respective loads).

Linearity tests were performed by applying a constant differential pressure across the box. The steps in the test procedure were:

1. Actuator pressure was set to the minimum value specified by the manufacturer.

2. Several differential pressures within the specified range were chosen as test points.

3. Fan speed was increased to reach one of the selected differential pressures.

4. The system was allowed to stabilize, then readings were taken of differential pressure across the nozzle and of static pressure.

5. Actuator pressure was increased slightly.

6. The differential pressure readings were noted, and the fan speed was adjusted to bring the differential pressure back to its constant value.

7. The system was allowed to settle and readings were taken.

8. Readings were continued as described above, increasing the actuator pressure incrementally over the manufacturer's recommended actuator pressure range.

9. Tests were repeated at several constant differential pressures.

10. Flow rate versus actuator pressure was plotted. The ideal graph is linear, as illustrated in Figure 8.

Hysteresis

Hysteresis is a measure of the difference in VAV box performance while increasing the input versus decreasing the input; ideally, the amount of hysteresis should be quite small. Figure 9 shows an example. The absolute value of the vertical distance between any two points with the same x-coordinate (e.g., points A and B) is the quantitative measure of hysteresis used to compare the boxes.

Hysteresis was examined for both the pressure independence and linearity tests. Hysteresis tests were identical to the previous tests, except that after the maximum input value was reached, measurements were also taken as the input was decreased incrementally. Plots of the data showed that the boxes tested had some hysteresis.

4 RESULTS

Pressure Independence

The boxes from manufacturer A were rated to give a flow rate of 30 to 250 cu ft/min (14 to 118 L/s) and were rated for a differential pressure of 0.4 to 3.0 in. water gauge (100 to 747 Pa). Tests indicated that the actual operating volume flow rate range was 80 to 360 cu ft/min (38 to 170 L/s). For actuator pressures of 8 to 10 psi (55 to 69 KPa), the deviation of data from a mean line was small, indicating very good pressure independence. However, at 11 to 13 psi (76 to 90 KPa), the boxes tended to let flow climb considerably and then taper off, producing a "hump" in the graph. This "hump" was quite pronounced for 13 psi (90 Pa), where the standard deviation from the mean line was as high as 53 cu ft/min (25 L/s). Figure 10 helps illustrate the behavior of these boxes. Using these boxes would probably be difficult because of the nonconstancy of the flow rate at higher actuator pressures.

To obtain better results, several other tests were performed to examine the characteristics of the spring and cone type arrangement. Changing spring constants did not seem to improve the test results much. Upon disassembling the spring and cone mechanism, a great deal of abrasion was noted between the mechanism and the box; however, cleaning the contact area and reducing the amount of the contact area by sanding did not seem to reduce the problem. Problems with this box were so great that it was deemed unlikely to function properly in a VAV system; therefore, tests on this box were discontinued.

The boxes from manufacturer B were rated for use between 0.2 and 3.0 in. water gauge (50 to 747 Pa), and for flow rates between 50 to 480 cu ft/min (24 to 227 L/s). However, in reality, rating these boxes for a minimum of 0.2 in. water gauge (50 Pa) seems quite questionable, since tests show that they did not reach a constant flow until about 0.8 in. water gauge (199 Pa). The actual operating flow rates were found to be 140 to 420 cu ft/min (66 to 198 L/s). These boxes deviated very little from the mean lines, with standard deviations ranging from 2 to 20 cu ft/min (0.94 to 9.4 L/s). Figure 11 illustrates the excellent pressure independence characteristics of a box from manufacturer B.

Manufacturer C rated its boxes for pressures of 0.4 to 3 in. water gauge (100 to 747 Pa) and flow rates between 0 and 320 cu ft/min (0 to 151 L/s). The actual operating flow rates for these boxes were found to be about 35 to 270 cu ft/min (17 to 127 L/s). The calculated standard deviations of these boxes were small, ranging from 2 to 23 cu ft/min (0.94 to 10.8 L/s). However, worse deviations seemed to occur in the middle of the actuator spectrum, rather than at the high or low end of actuator pressures. In the middle of the actuator spectrum, the data tended to form "humps," but they were not of the magnitude of those observed for manufacturer A. Also, in the middle of the spectrum, a gap appearing between data lines shows that the constant flow rates corresponding to evenly spaced actuator pressures are not evenly spaced. Figure 12 illustrates the behavior of this VAV box.

Linearity

Boxes from both manufacturers B and C showed fairly linear characteristics over the specified actuator pressures. The standard deviation of data from a fitted line

ranged roughly from 5 to 20 cu ft/min (2.4 to 9.4 L/s). Figure 13 shows an example of a set of typical linearity data.

Pressure Independence and Hysteresis

The mean difference in flow for a given actuator pressure during increasing versus decreasing actuator pressure (a measure of hysteresis) for boxes from manufacturer B was much higher than that for boxes from manufacturer C. The pattern of hysteresis for boxes from manufacturer B was also very consistent over the tested ranges. A statistical analysis of variance showed that data from different boxes from manufacturer B did not differ greatly. Each box showed essentially the same pattern of hysteresis. Figure 14 shows an example of pressure independence and hysteresis for a box from manufacturer B. Boxes from manufacturer C had much lower mean differences, and thus less hysteresis; the statistical analysis of variance showed that the mean differences recorded for each box varied greatly over the range of the tests. This is a good indicator that the role of hysteresis in the characteristics of this box is small, since the amount of hysteresis measured was small and random. Figure 15 illustrates the randomness of hysteresis for a box from manufacturer C by using two sample data sets (one set of increasing values corresponding to two sets of decreasing data values); it also helps show the magnitudinal differences between the hysteresis for boxes from manufacturer B (Figure 14) and manufacturer C.

Linearity and Hysteresis

Boxes from manufacturers B and C showed consistent hysteresis with respect to actuator pressure. There was no statistical difference between the results over the range of tests. The mean difference encountered (again, a measure of hysteresis) was in the range of 20 cu ft/min (9.4 L/s). Figure 16 illustrates a typical linearity and hysteresis plot.

General Observations

The results of these tests indicate that performance characteristics of available VAV boxes vary widely. Although there are standard testing procedures available to evaluate box performance, they are not widely used by manufacturers, and it seems likely that the wide variation among manufacturing standards will continue. If designers begin to require certification of boxes, perhaps manufacturers will begin to improve box performance. The Air-Conditioning and Refrigeration Institute in Arlington, VA, is implementing a certification program.

The tests showed that most of the boxes do not quite meet the manufacturers' performance claims. For example, no box reached its specified performance level for differential pressure rating (e.g., constant flow) until roughly 0.8 in. water gauge (199 Pa); however, these boxes were supposed to provide constant flow at pressures of 0.2 to 0.5 in. water gauge (50 to 125 Pa). If certification becomes more common, ratings would probably become much more accurate.

The appearance of a "hump" in the pressure independence curves of some boxes, most notably from manufacturer A, has serious implications for use in HVAC applications. During initial startup of the system on a day when cooling loads are heavy, all boxes would be functioning fully open; that is, they would be functioning at an

actuator pressure of 13 psi (90 KPa), where its lack of pressure independence was shown to be at its worst. Because of this box's heavy flow rate requirements in this region, the cool air would be directed heavily into the first zones, while zones served downstream in the ductwork would receive very little cool air. The problem is serious enough to make use of this box very difficult.

Another problem with all boxes was their inability to conform to the specified minimum and maximum flow rates. It is possible to recalibrate these boxes to give desired flow rates, but such calibrations would likely be difficult and time-consuming to perform in the field.

The use of VAV systems in day-to-day HVAC applications is looking increasingly attractive; however, to use VAV technology effectively, users must ensure that all devices in the system function as expected. Once testing and rating of thermostatically controlled air-modulating boxes become standardized, these boxes will be extremely useful in helping to make VAV systems functional, dependable, and efficient.

5 CONCLUSIONS AND RECOMMENDATIONS

Measurements of the performance characteristics of VAV boxes from three manufacturers provided the following results:

1. The VAV box with a butterfly damper and inflatable bladder type of setup (from manufacturer B) showed excellent pressure independence characteristics. The box with a guillotine-type blade with a bellows (from manufacturer C) also performed well except in the middle of the actuator spectrum. The worst performance was demonstrated by the spring and cone type system (from manufacturer A), which showed such pronounced deviations that it was thought to be unlikely to function properly in a VAV system.

2. Boxes from manufacturers B and C showed fairly good linearity characteristics.

3. Boxes from manufacturer C showed the best performance for hysteresis characteristics, showing very little mean difference in performance. However, data for boxes from manufacturer B were also quite consistent, showing the same type of hysteresis patterns.

4. Observations of the overall test results indicated that the performance characteristics of VAV boxes vary widely and that this variation is likely to continue until consistently applied manufacturing standards are implemented. Also, the tests showed that most VAV boxes do not quite meet the manufacturers' performance claims. A general problem is the boxes' inability to conform to specified minimum and maximum flow rates; although recalibration to give the desired flow rates is possible, it would be a difficult, time-consuming procedure in the field.

Since the immediate resolution of the problems with VAV boxes by the manufacturers seems unlikely, actions are required during HVAC system design and commissioning to accommodate less-than-perfect VAV box performance. Due to the problems with the boxes' inability to meet their specified minimum and maximum flow rates, designers should keep in mind that they will require field calibration in order to function properly.

Also, since the boxes require a higher static pressure in the ducts than the manufacturer specifies, a system should be used that can supply and function with a static pressure of roughly 1 in. water gauge (249 Pa). Boxes with more complex control schemes should be tested to see if they are a better choice for VAV applications.

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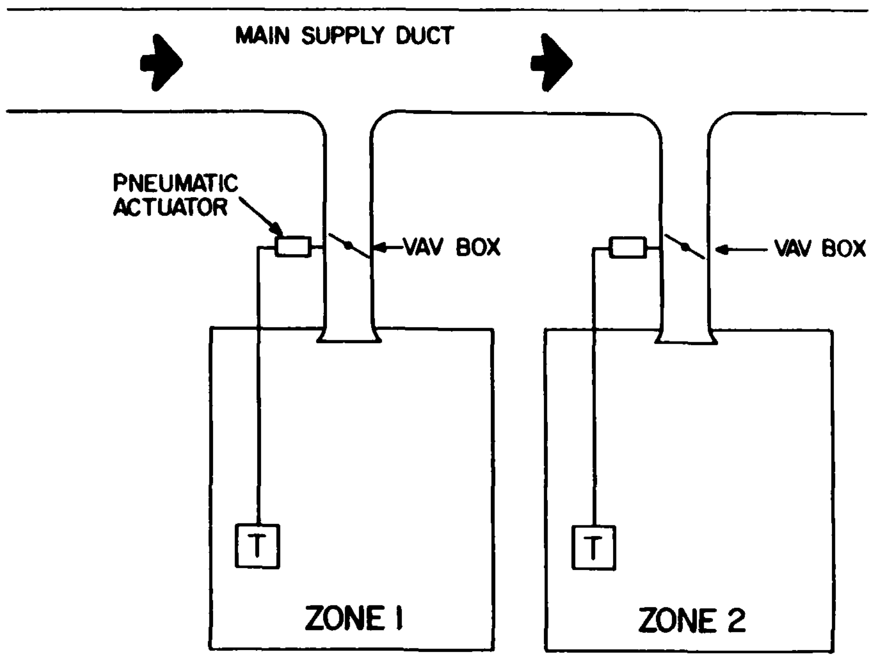

Figure 1. Basic VAV box configuration.

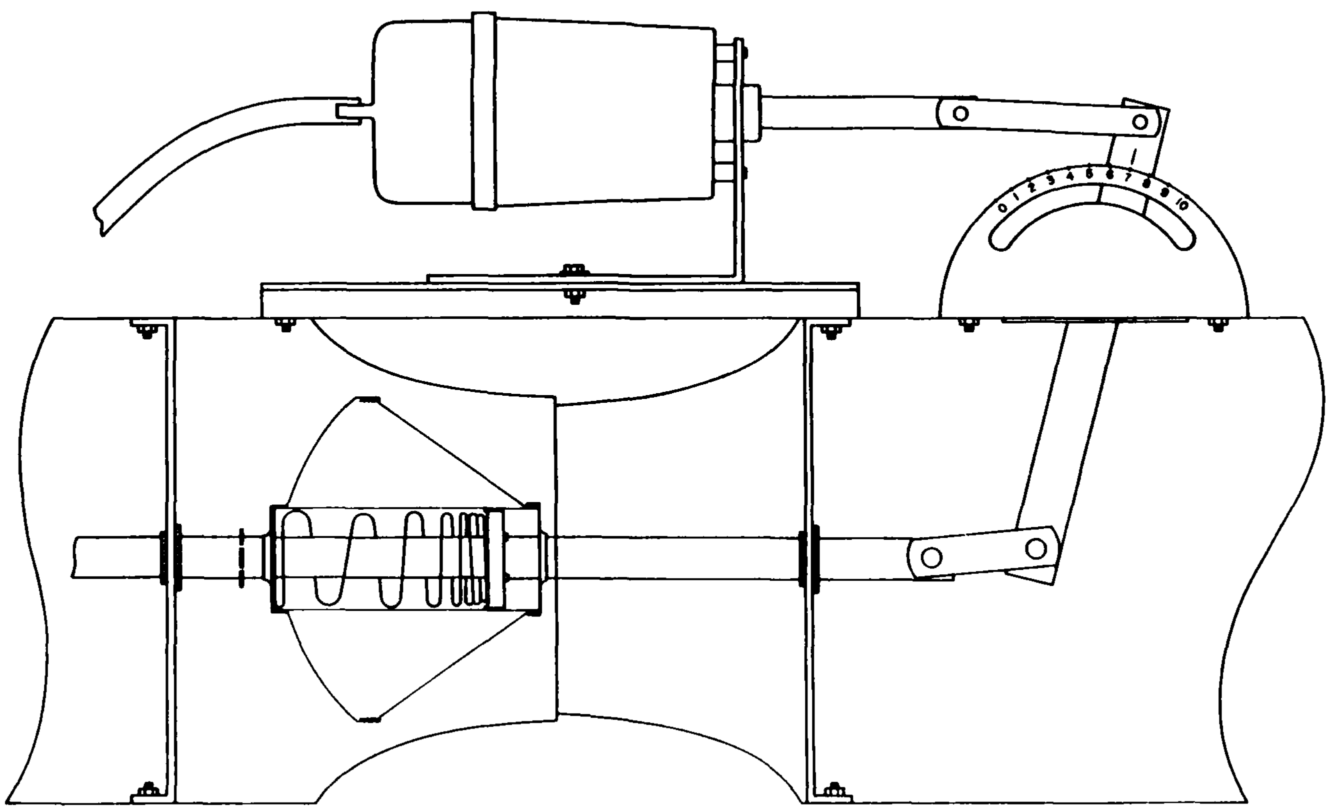

Figure 2. Spring and cone type box.

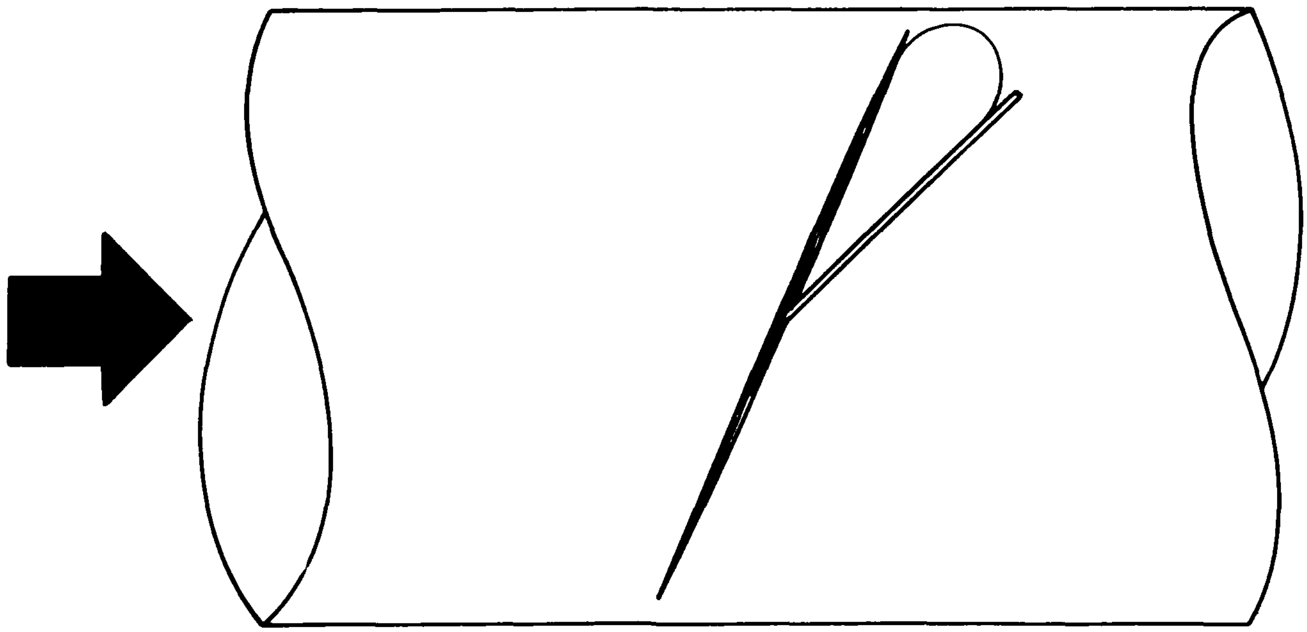

Figure 3. Butterfly damper and inflatable bladder type box.

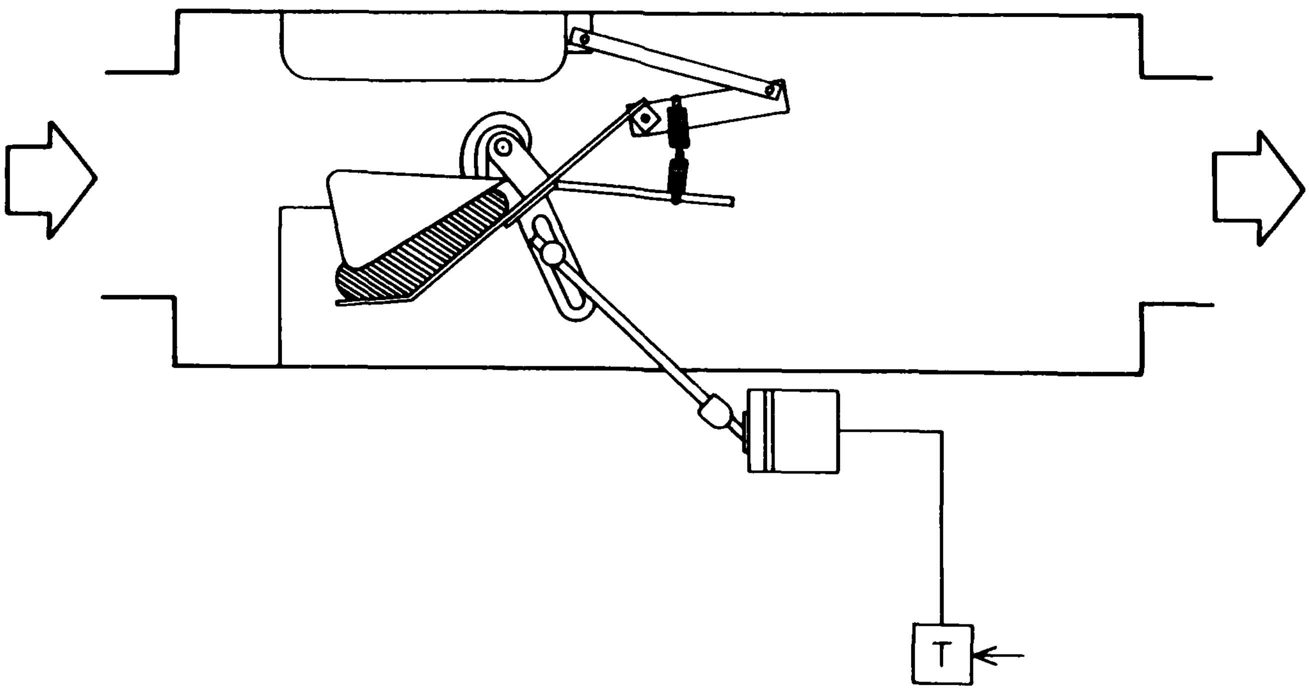

Figure 4. Guillotine blade type box.

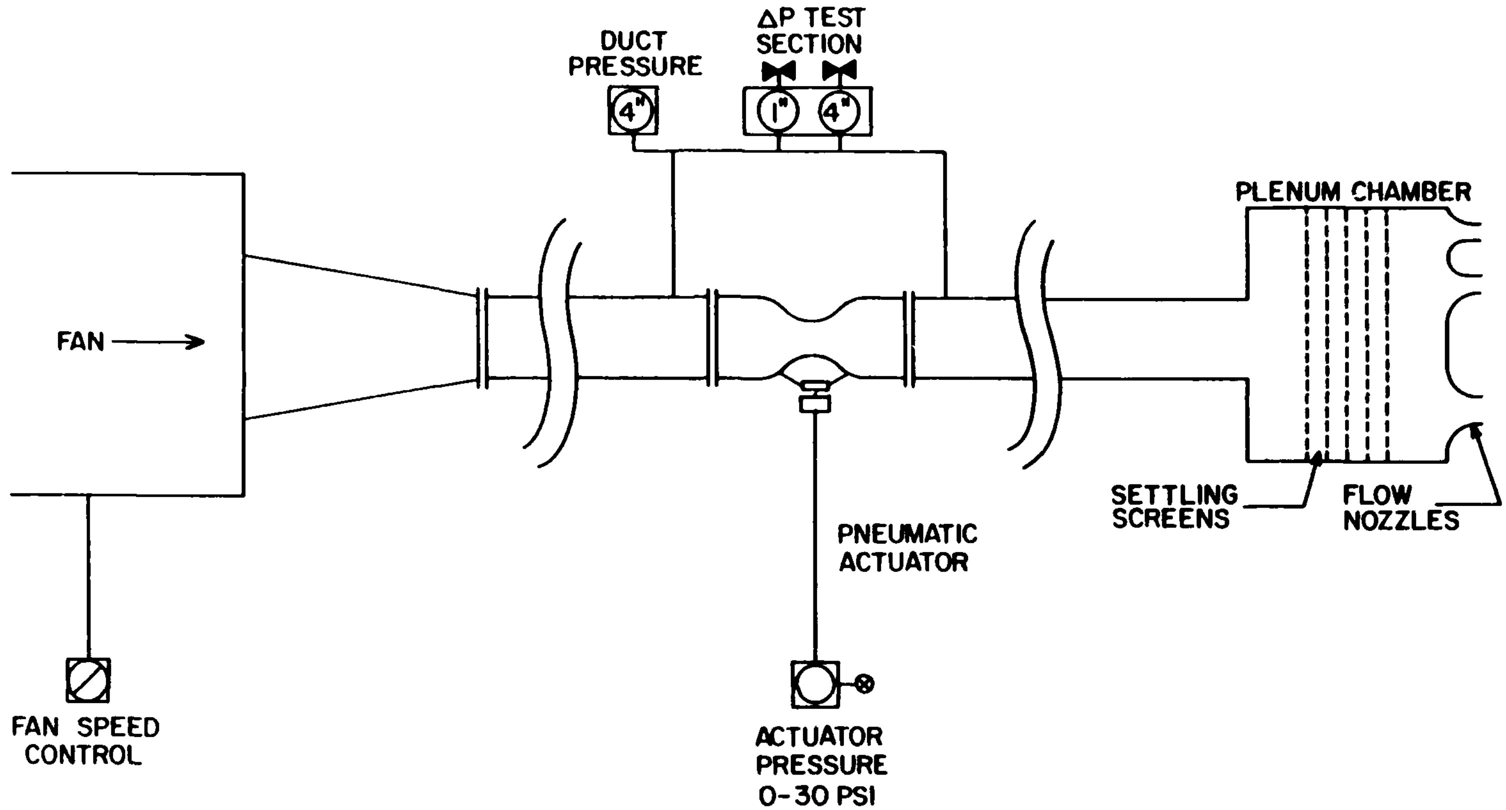

Figure 5. Test apparatus.

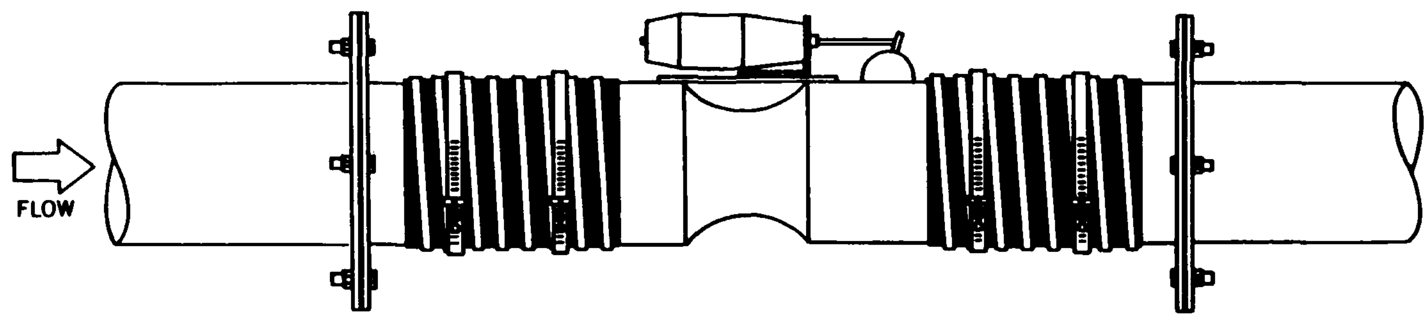

Figure 6. Removable VAV box assembly.

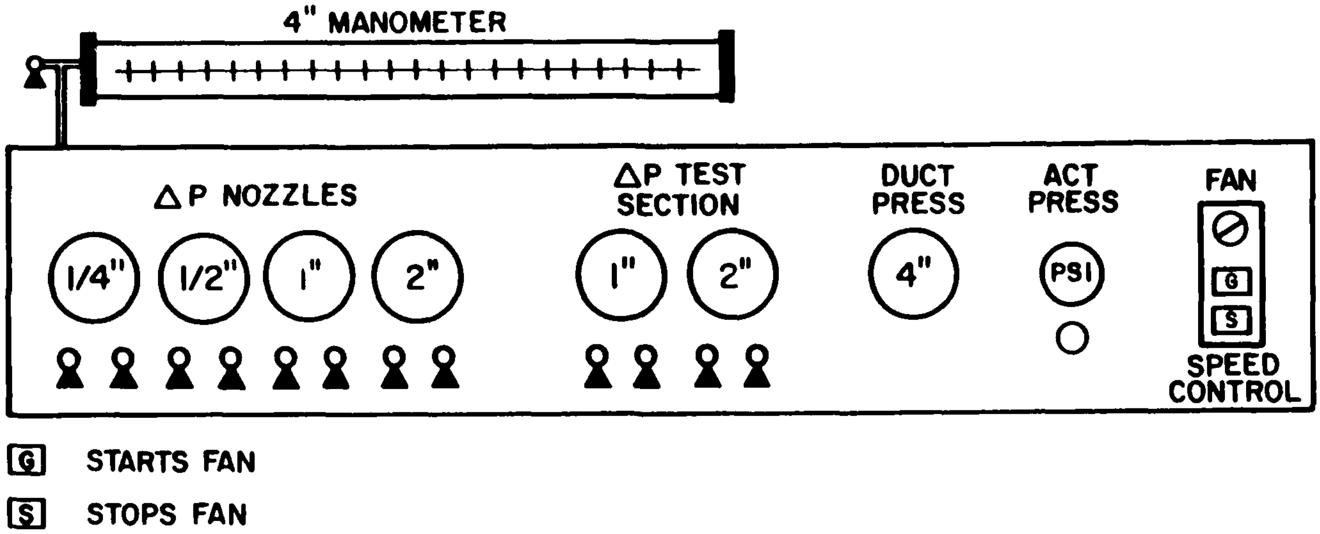

Figure 7. Testing apparatus control panel.

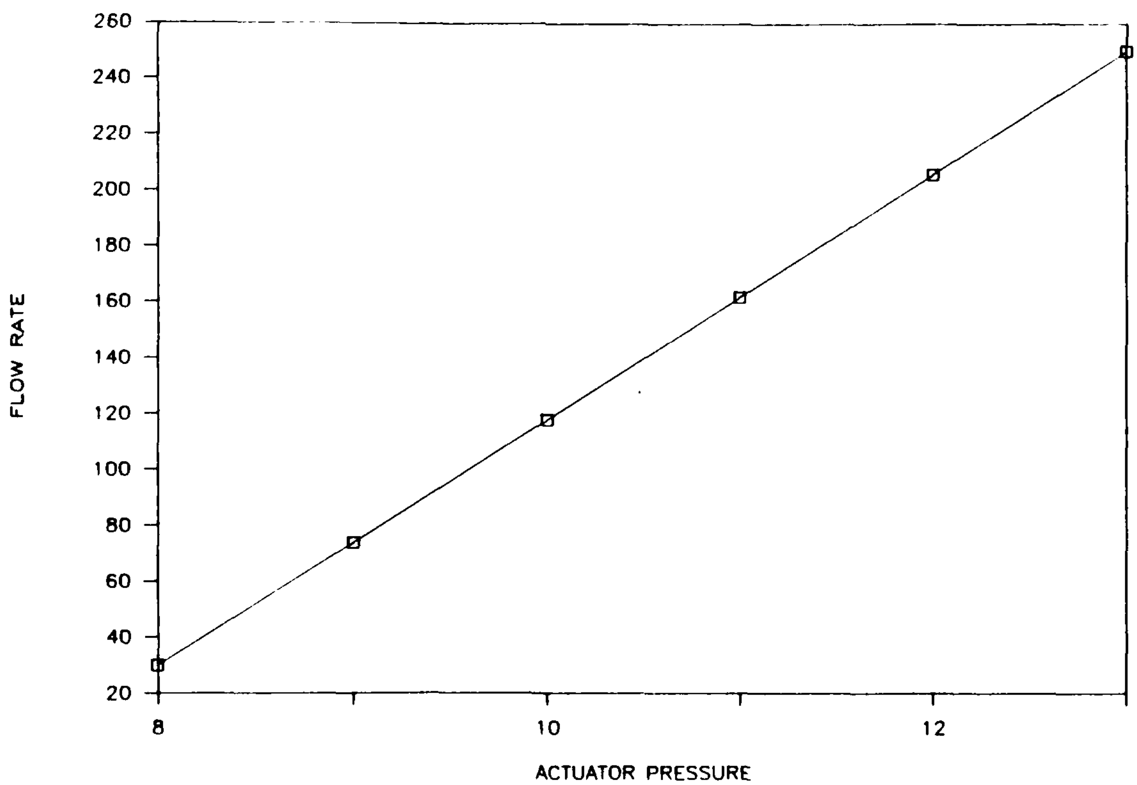

Figure 8. Ideal linearity.

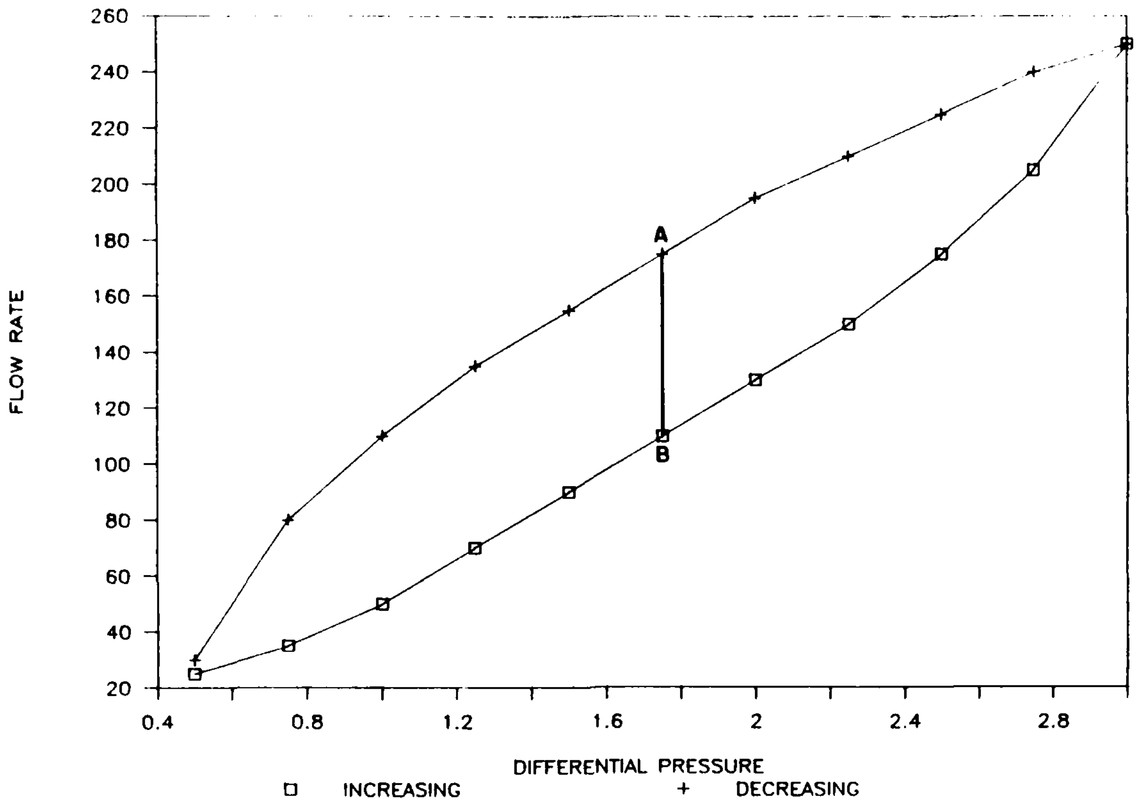

Figure 9. Hysteresis example.

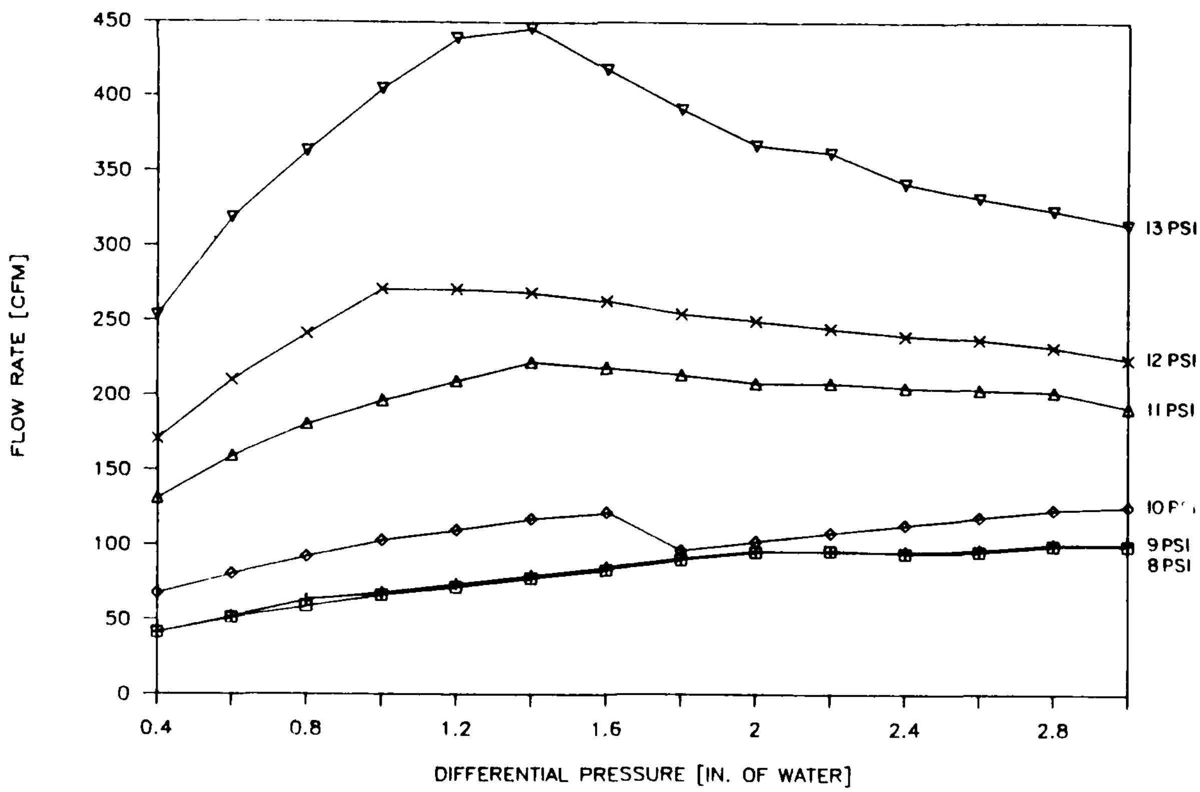

Figure 10. Pressure independence, manufacturer A.

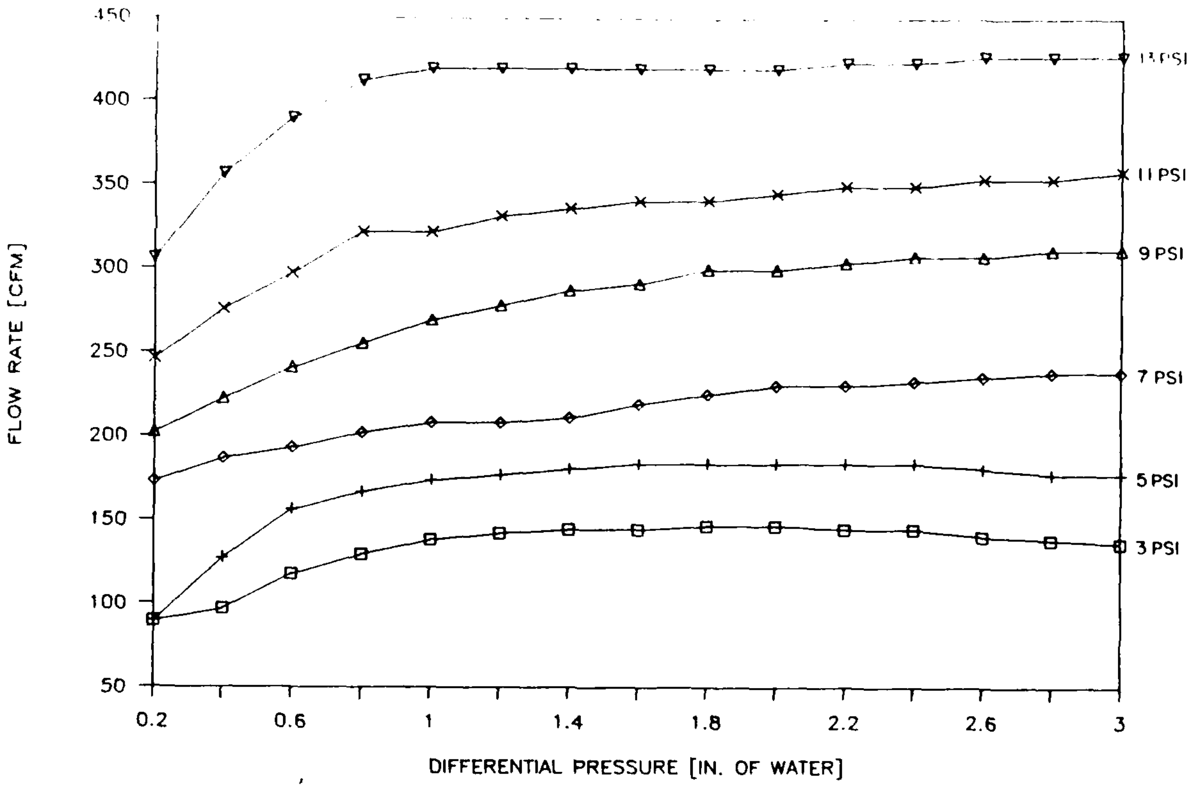

Figure 11. Pressure independence, manufacturer B.

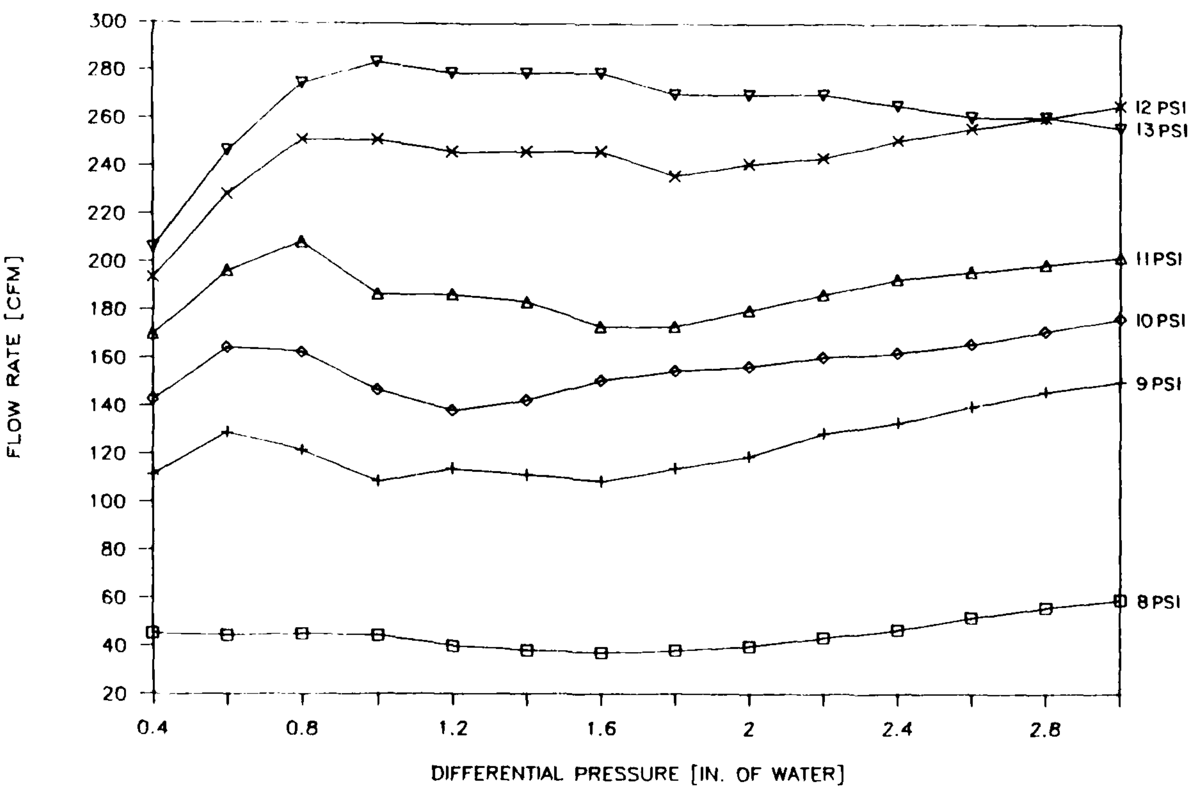

Figure 12. Pressure independence, manufacturer C.

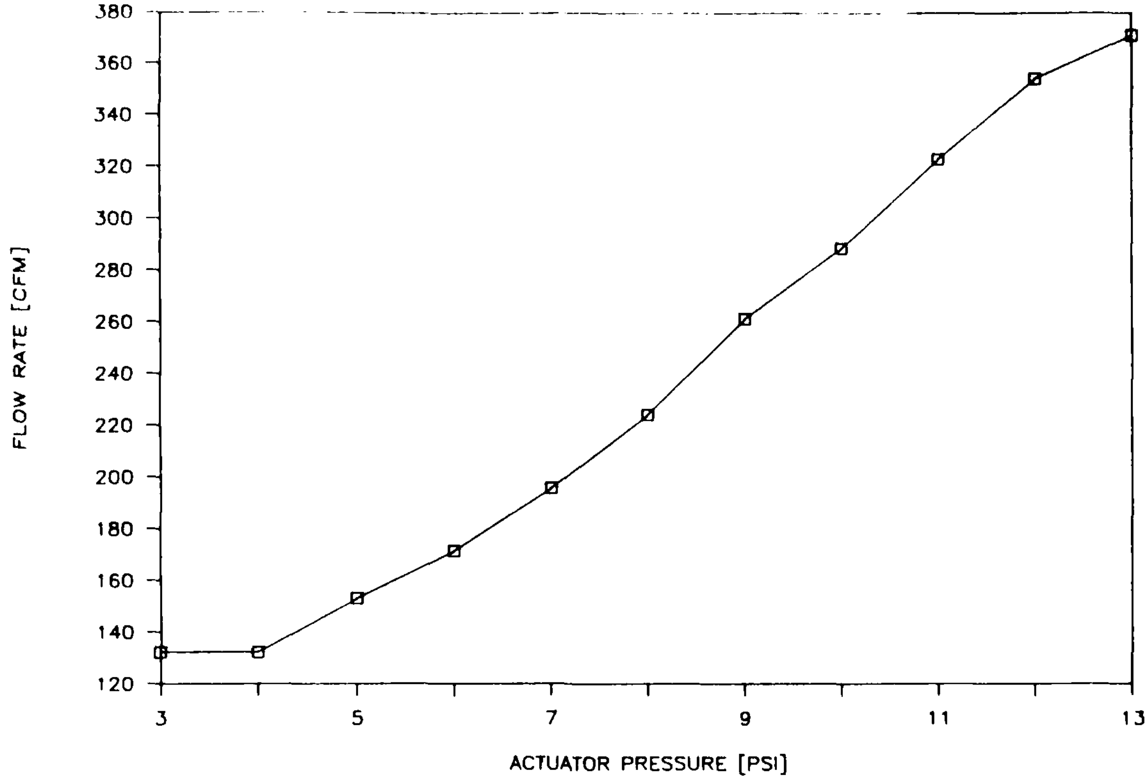

Figure 13. Linearity at 3-in. water gauge, manufacturer B.

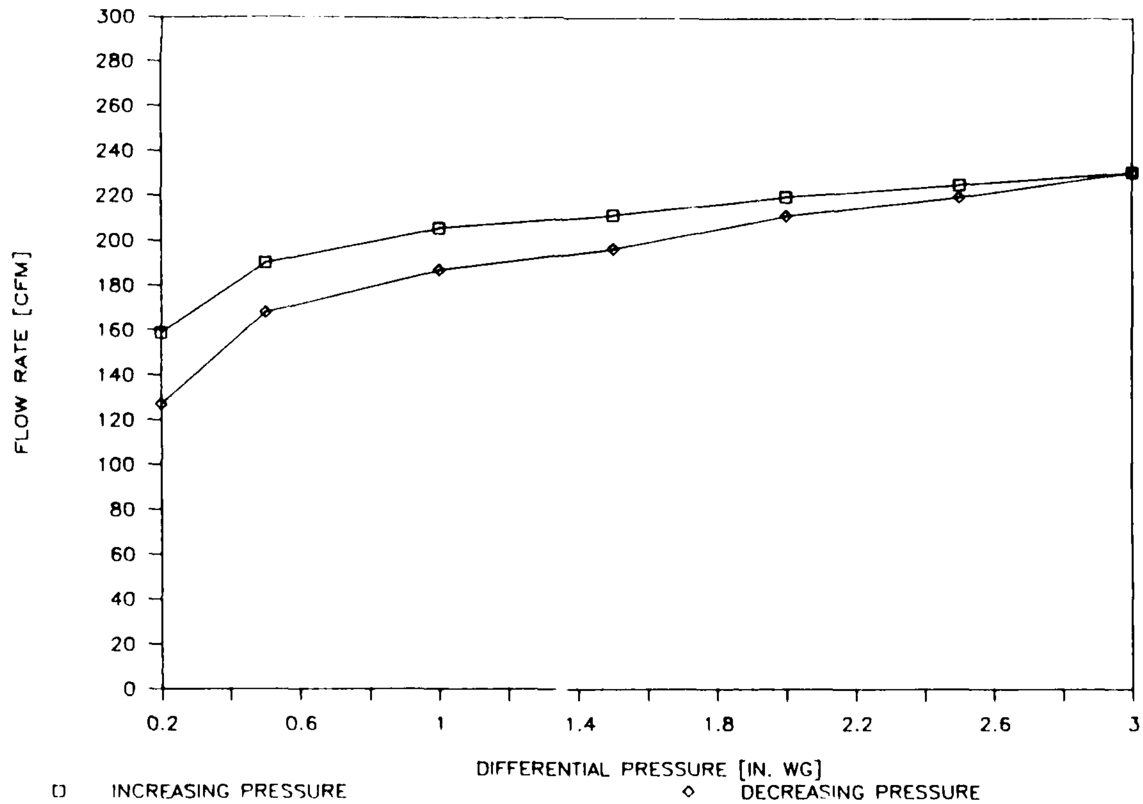

Figure 14. Pressure independence and hysteresis, manufacturer B.

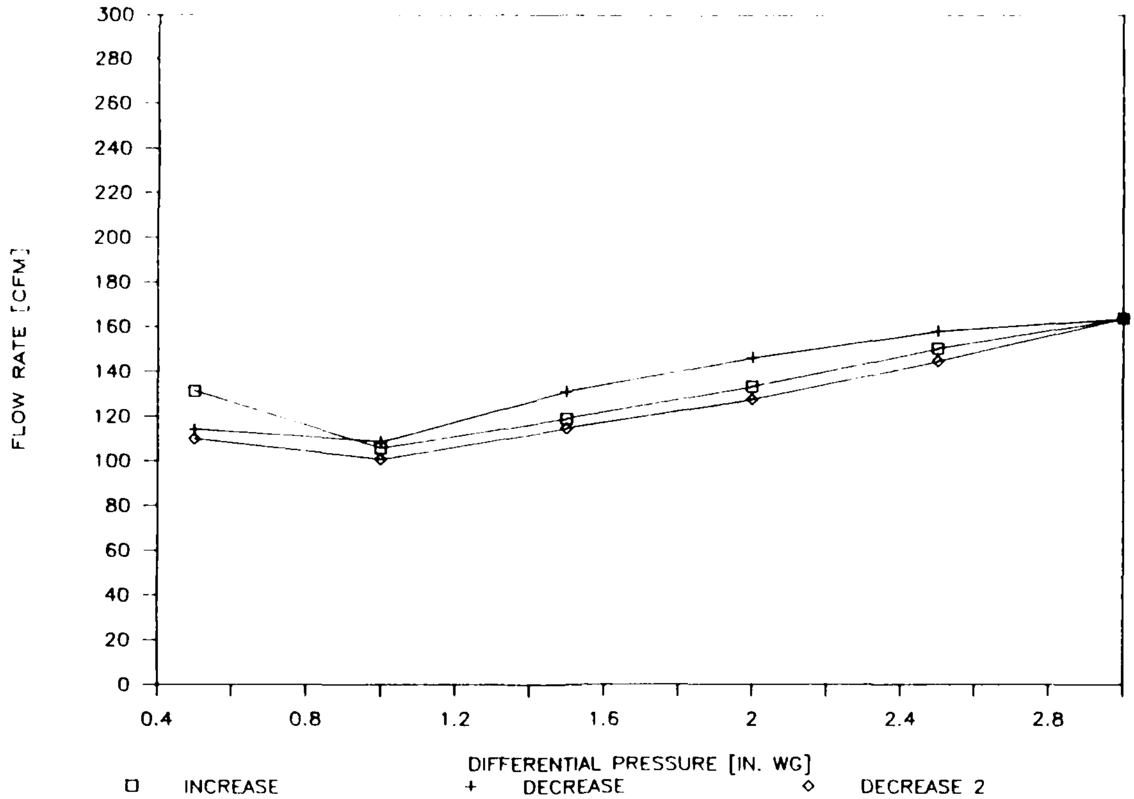

Figure 15. Pressure independence and hysteresis, manufacturer C.

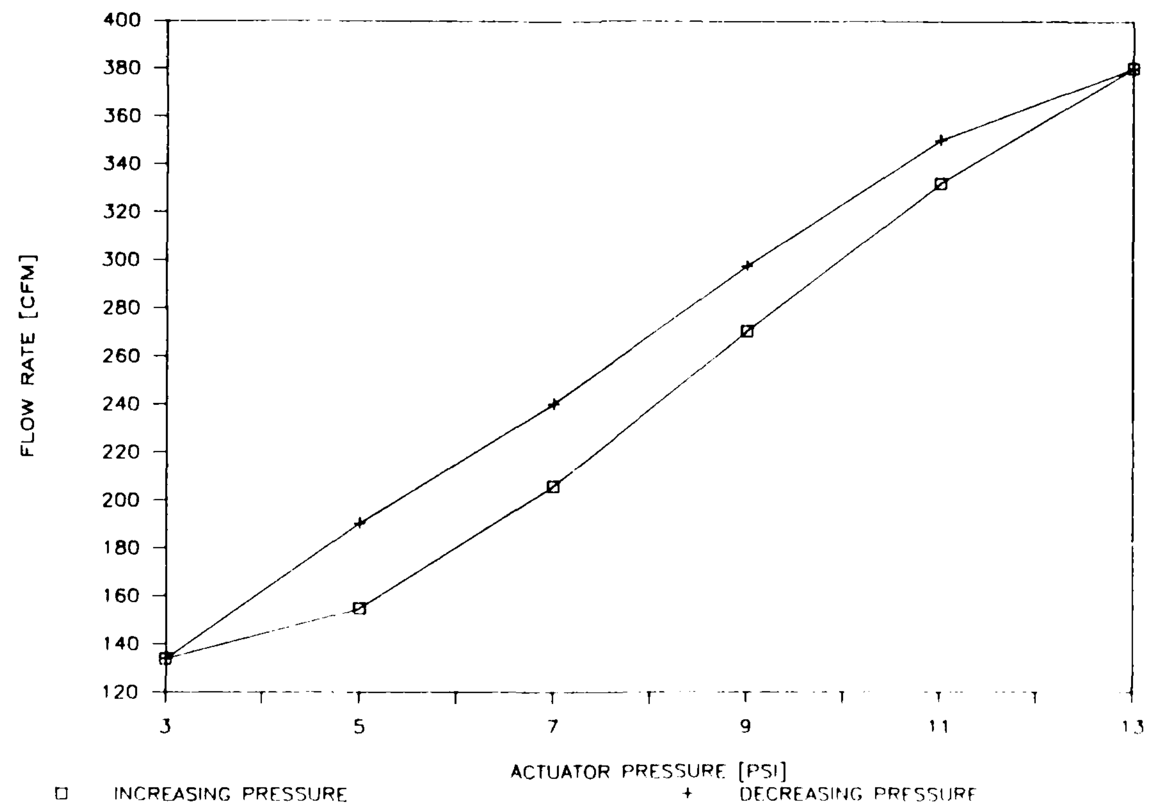

Figure 16. Linearity and hysteresis, manufacturer B.

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